NASA Contractor Report 3220

Selected Advanced Aerodynamic and Active Control Concepts Development - Summary Report

CONTRACT NAS1-14742
JANUARY 1980

NASA

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Selected Advanced Aerodynamic and Active Control Concepts Development - Summary Report

Boeing Commercial Airplane Company
Seattle, Washington

Prepared for
Langley Research Center
under Contract NAS1-14742

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Office

1980

FOREWORD

This document constitutes the summary report of work conducted under NASA contract NAS1-14742 during the period August 10, 1977 through May 1, 1979. The contract was managed by the NASA Energy Efficient Transport Project Office (EETPO) headed by Mr. W. J. Alford, a part of the AirCraft Energy Efficiency (ACEE) Program organization at the Langley Research Center. Mr. D. B. Middleton of the EETPO was technical monitor for the contract. The contract was performed within the Preliminary Design Department of the Boeing Commercial Airplane Company Vice President-Engineering Organization. Key Contractor Management personnel responsible for conduct of the six contract tasks were as follows:

Glen W. Hanks	Program Manager
Project Managers:	
C. W. Clay	Natural Laminar Flow
Richard L. Kreitinger	Surface Coatings
Ralph L. Erwin	Integrated Energy Management
Jerry L. Lundry	High Lift Concepts
Henry A. Shomber	Integrated Application of Active Controls
Gerry L. Katt	747 Primary Flight Control Systems Reliability and Maintenance

Under subcontract, Eastern Airlines and United Airlines provided consultant reviews of the contract work results, as they would affect airline operations. United Airlines also conducted specific studies toward defining technical requirements. In addition, a large part of the surface coatings work was performed under subcontract by the Avco Corporation. Continental Airlines participated in a flight service evaluation of surface coatings.

Principal measurements and calculations used during these studies were in customary units.

NOTE: Certain commercial materials are identified in this paper in order to specify adequately which materials were investigated in the research effort. In no case does such identification imply recommendation or endorsement of the product by NASA or Boeing, nor does it imply the materials are necessarily the only ones or the best available for the purpose.

CONTENTS

SUMMARY

Under the EET Phase I program Contract NAS1-14742, exploratory investigations were made into six technical subjects. These subjects offered potential fuel savings through technology advancements that could be applied to the design and operation of future transports. The objective was to identify those that offered high payoff potential, and to determine the direction of Phase II work to establish needed state-of-readiness for application by industry.

Significant findings were:

- Three subjects were identified as deserving further development during Phase II.
  - Airfoils that offer the potential for natural laminar flow up to 50% chord were theoretically defined and exploratory configuration work was conducted. Further configuration work is needed. Flight test by the NASA, or under Phase II contract effort, is recommended to prove the theoretical results.
  - Two surface coatings were identified that offer good potential for reducing drag and leading edge erosion. Limited flight evaluation of those coatings was started. Phase II work should concentrate on process improvement, procedures for application to large surfaces, drag measurement, and large scale flight evaluation.
  - Application of active controls during the preliminary design process, where maximum payoff can be expected, was evaluated and a long-range program was identified. Work was initiated on early activities of that plan. This subject should be pursued to the maximum extent permitted by Phase II funding availability.
- The feasibility of an integrated energy management system for minimum energy flight profile, was established. The system used on-board and flight sensor data as input to computer control of autothrottle and autopilot. Industry can proceed with the concept without further NASA support.
- Airplane performance improvement, by appliction of new performance evaluation techniques applicable to high lift devices at high Reynolds numbers, was evaluated. Refinement of techniques and proof of theory should proceed through joint NASA/industry efforts as R&T base type research activities.
- Operating airline historical component failure, repair and maintenance data on the 747 Primary Flight Control System were evaluated. These data provide a sound base for evaluation of the potential reliability and cost of ownership of advanced flight control systems. Refinement of implementing techniques should be pursued through joint NASA/industry participation under R&T base type research activities.

INTRODUCTION

During coordination between NASA and the contractor early in the ACEE/EET program, several technical subjects were identified that offered fuel savings potential and could influence the design and operation of future transports. Participation by the contractor during Phase I of the EET Program was directed toward exploration of the technical feasibility, fuel savings, and economic benefits of seven subjects offering the highest potential. The objective was to identify candidates that deserved more intensive investigation and/or development during Phase II. One exploratory effort, conducted as Program I under Contract NAS1-14741, evaluated the potential offered by application of wing load alleviation (WLA) and wing-tip extensions or winglets on the Model 747 transport. The results of that work are reported separately (ref. 1).

Under Contract NAS1-14742, the subject of this report, investigations were conducted in the six individual task areas described on the next page. The six tasks covered a wide range of technical interest. This report provides a summary of the objectives, approach, results obtained, and recommendations for future effort in each task area.

CONTRACT SCOPE/SCHEDULE

Contract NAS1-14742 was the Program II portion of a two-part Phase I EET program conducted by the contractor. A separate Program I involving the Model 747 was conducted under Contract NAS1-14741 (ref. 1). The investigations under Contract NAS1-14742 were exploratory in nature, aimed at determining the technical feasibility and desirability of proceeding further in each of the six technical subjects listed in Figure 1, all of which offered fuel savings potential. The subjects fell into two general advanced technology categories. The scope of each investigation is summarized below:

AERODYNAMICS

- Natural Laminar Flow: Analytical studies to establish airfoil designs that offered potential for obtaining laminar flow over a large portion of a transport wing, and exploratory evaluation of transport configurations using those airfoils. Limited Phase II work is recommended.

- Surface Coatings: Laboratory environmental testing to establish candidate coatings and films that would reduce surface drag, and the initiation of in-service flight evlauation of high potential candidates. Phase II work is recommended.

- High Lift Concepts: Transport airfoil design and evaluation to establish the payoff of advanced analysis techniques applied to high lift airfoils at high Reynolds numbers. No Phase II work is recommended.

ACTIVE CONTROLS

- Integrated Energy Management (IEM): Analytical studies to establish the feasibility of and appropriate algorithms for closed-loop computer control of autopilot and autothrottle. The system studied used on-board and sensor data to attain minimum energy flight profiles. No Phase II work is recommended.

- Integrated Application of Active Controls (IAAC): Program planning and initiation of technical work to; (1) determine the benefits of active controls incorporated during the preliminary design phase to take maximum advantage of the potential performance improvement (weight reduction and improved lift/drag), and (2) begin definition and development of active control systems with reliability and dispatchability suitable for commercial transports. Major Phase II work is recommended.

- 747 Primary Flight Control System Reliability and Maintenance: Analysis of airline Model 747 system/component failure and maintenance cost data to establish a base for evaluation of advanced active control systems. No Phase II work is recommended.

Results of the five tasks completed during Phase I have been published in five contractor reports (references 2 through 6) as indicated in the figure on the following page. Phase II work has been initiated under Contract NAS1-15325.

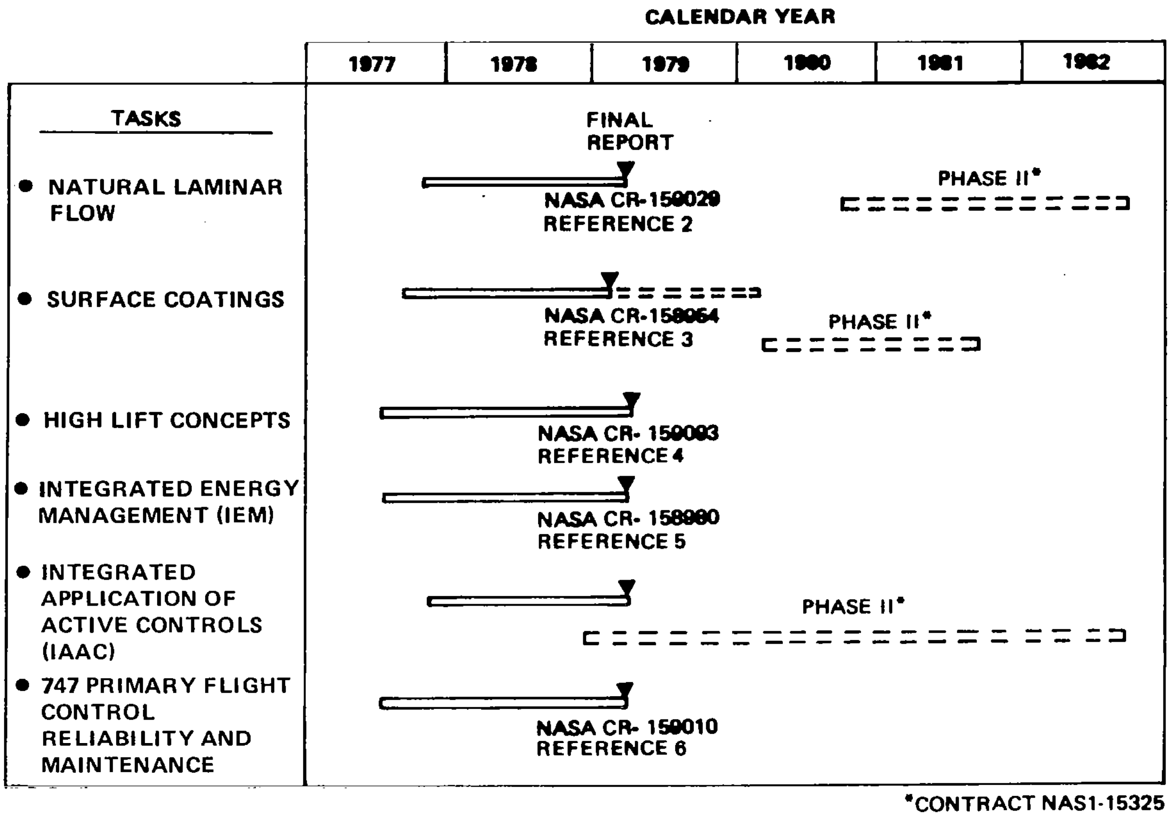


Figure 1. Contract NASA 1-14742 Tasks

NATURAL LAMINAR FLOW (NLF)

OBJECTIVE

Under this task, studies were performed to explore the application of natural laminar flow (NLF) technology to commercial transport aircraft. As shown by the solid dots in Figure 2, the goal was to attain laminarization up to 60% on the upper surface and 40% on the lower surface of a transport wing when operating at cruise Mach number of approximately 0.80. The intent was to apply modern analysis techniques toward defining airfoils optimized to yield maximum laminar flow and to identify their implications in transport design.

APPROACH

Results of contractor-funded analyses conducted prior to the contract indicated advanced analytical tools permitted airfoil design refinements offering high potential for attaining laminar flow much further aft of the leading edge than presently available. That conclusion assumed smooth and clean surfaces that would not trip the boundary layer. The contract studies extended the previous analysis toward refinement of candidate airfoils. They included exploratory investigation of the characteristics of transport configurations that utilized such airfoils.

AIRFOIL CHARACTERISTICS

In the airfoil design process, it was assumed that extended regions of favorable pressure gradient would correspond to extended regions of laminar flow. Also, to limit wave drag, the local Mach number was limited to a value less than 1.2. To ensure attached flow, the maximum slope of the aft pressure gradient, $\frac{dC_p}{d(x-c)_{max}}$ was to be less than 3.0. This led to the "starting airfoil" shown in Figure 2. The pressure profile of a typical advanced turbulent airfoil is shown for comparison.

Effects of increasing $(t/c)_{max}$ and off-design Mach number and lift coefficient on the extent of NLF and wave drag were evaluated. This evaluation was followed by airfoil modification to improve the operating boundaries. The final airfoil was the fourth iteration in this refining cycle. Transition points were determined by subsequent boundary layer stability analysis. Transition on the final airfoil was predicted to occur at 35% and 50% on the upper and lower surfaces respectively, as shown by the solid circles in Figure 2. The absolute goals for the upper and lower surfaces were not attained. However, the study verified that through iterative use of advanced boundary layer flow analysis and stability calculations, an airfoil providing a high degree of natural laminar flow can be designed. Further iterations could improve the airfoil still further.

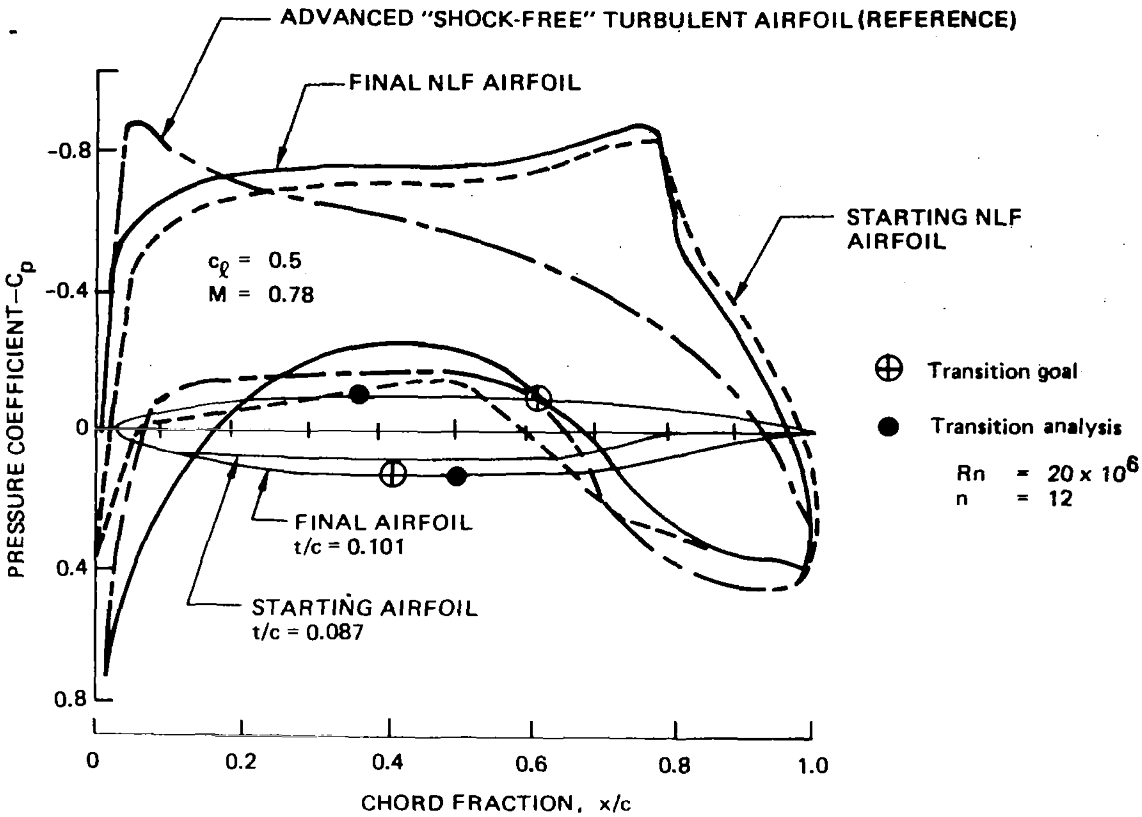


Figure 2. NLF Airfoil Pressure Profiles

NATURAL LAMINAR FLOW
AIRFOIL APPLICATION AND DESIGN CONSTRAINTS

Practical, operational application of NLF by the airlines will require satisfactory operation over a broad speed range, rather than a specific design point speed. The final airfoil met that requirement as indicated by the unshaded area of Figure 3. It was predicted that the final NLF airfoil would yield a satisfactory theoretical range of NLF application at a M = 0.78, C_{ℓ} = 0.5 design point. It was also determined that laminarization could be maintained at lower speeds with proper attention to flight conditions.

Results of a leading-edge-sweep study are shown in Figure 4. Early transition can be caused not only by surface irregularities and adverse pressure gradient, but also by boundary-layer crossflow instability. A wing sweep and boundary-layer stability analysis, based upon a representative pressure distribution, revealed that crossflow instability could cause transition on natural laminar flow airfoils at very low sweep angles, depending on airfoil pressure gradient. For the particular pressure distribution used in the present analysis, crossflow was found to cause transition for leading-edge sweep angles larger than 0.22 rad (7 deg), as shown in Figure 4.

However, a different airfoil pressure gradient could allow a higher leading-edge sweep but also adversely affect the Tollmien-Schlichting stability. The integration of a natural laminar flow airfoil into a three-dimensional swept wing is a very complex task requiring in-depth studies of optimum pressure distribution versus sweep angle, Reynolds number effects, and Mach number effects. Since such in-depth studies were beyond the scope of the contract, it was necessary to choose a leading-edge sweep angle that would provide some margin from crossflow instability, based upon the representative distribution developed for this study. Therefore, a leading-edge sweep angle of 0.09 rad (5 deg) was chosen for the airfoil study.

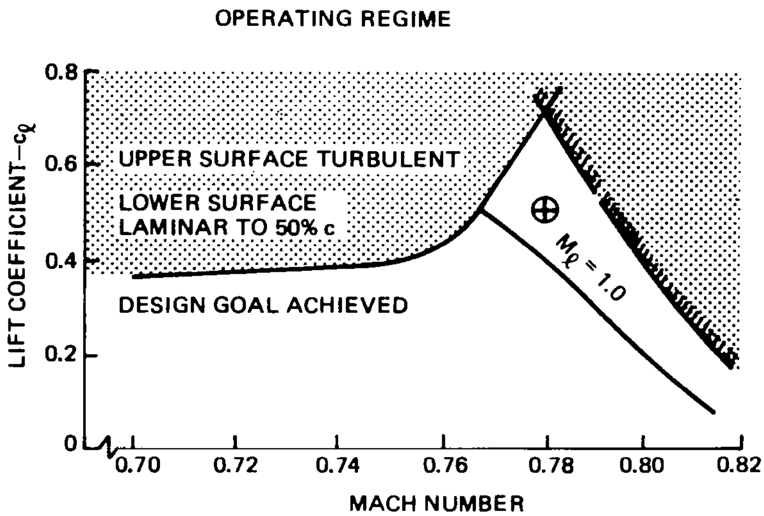


Figure 3. Selected Airfoil Operating Regime

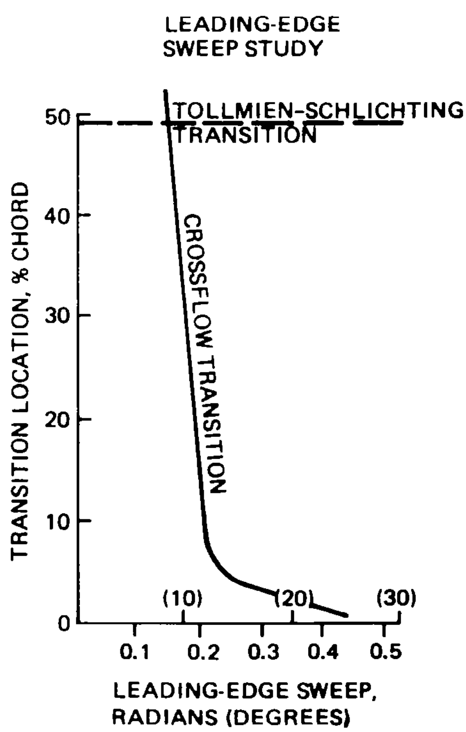


Figure 4. Transition Versus Wing Sweep

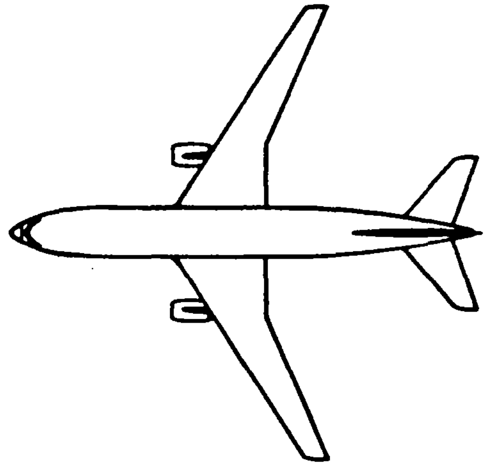
NATURAL LAMINAR FLOW CONFIGURATION DEFINITION

Exploratory studies were conducted to determine the implication of the NLF concept to transport configuration design. A 200-passenger, 3704km (2000 nmi) mission was selected as a basis for definition since it represented a needed market requirement and an opportunity for significant fleet-wide fuel savings. The resulting NLF transport was compared for the same mission with a well-defined conventional twin-engine turbulent airplane.

The reference turbulent airplane, shown in Figure 5, was of conventional skin/stringer design, using an AR = 10.24 wing swept 0.52 rad (30 deg), leading-edge devices, and two wing-mounted engines. Wing thickness varied from 10.3% at the tip to 15% at the body juncture to yield high structural efficiency. This configuration had received extensive optimization during its conceptual definition phase.

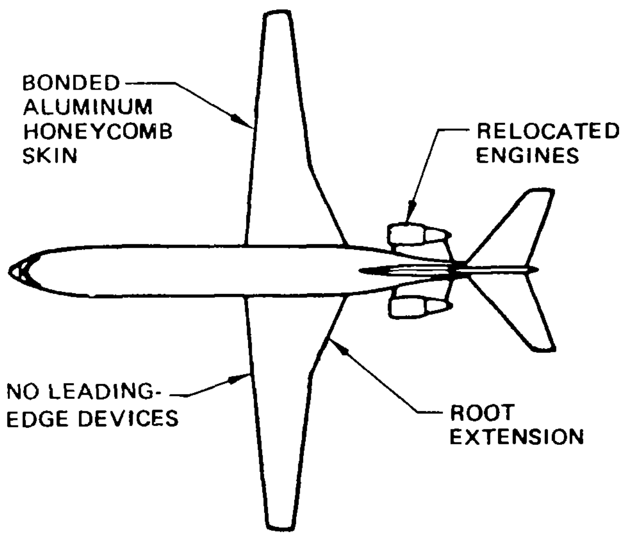
The NLF airplane, shown in Figure 6, utilized a nearly straight 0.04 rad (2.5 deg) wing of essentially constant low thickness ratio (tip = 10.1%, body juncture = 11%) to ensure natural laminar flow. Aft-mounted engines were used to prevent engine noise or nacelle pressure fields from prematurely tripping the wing boundary layer. To preclude surface discontinuities, no leading-edge devices were included. Bonded aluminum honeycomb wing skins were used to obtain maximum surface smoothness, and a large trailing-edge extension was required to accommodate the landing gear. The wing was found to be gust-critical.

The combination of low thickness at the wing root, very low sweep and low speed operations with no leading-edge devices selected for the final NLF configuration, resulted in a relatively large wing area and high structure weight, compared to the turbulent reference configuration.



- c/4 sweep = 0.52 rad (30 deg)
- AR = 10.24
- S_w = 235.5 m^2 (2 535 ft^2)
- t/c: = tip 0.103, root 0.15

Figure 5. Turbulent Reference Airplane



- c/4 sweep = 0.04 rad (2.5 deg)
- AR = 10.24
- S_w = 309.8 m^2 (3 335 ft^2)
- t/c: tip 0.101, root 0.11

Figure 6. Natural Laminar Flow Airplane

NATURAL LAMINAR FLOW STUDY EVALUATION

PERFORMANCE

The NLF airplane showed a substantial lift-to-drag (L/D) improvement in performance over the turbulent reference airplane. However, the advantage of improved L/D for the NLF configuration was found to be negated by nearly an equal percentage increase in airplane weight. Because of this, the block fuel and reserve fuel requirements were also greater for the NLF airplane. The increased fuel requirement and slightly slower cruising speed of the NLF airplane resulted in a direct operating cost greater than that of the turbulent reference airplane.

CONCLUSIONS

The study demonstrated that the combination of boundary layer stability analysis techniques with standard airfoil design techniques can be used to satisfactorily define a two-dimensional airfoil having natural laminar flow over a major portion of a wing chord typical of a large contemporary civil transport. However, the integration of such an airfoil into a three-dimensional swept wing is the most challenging problem to be solved before natural laminar flow can be successful.

The basic problem involved in obtaining natural laminar flow on a swept wing, as opposed to an unswept wing, is that the two basic types of laminar boundary layer instabilities which occur on a swept wing (crossflow instability and Tollmien-Schlichting instability) are affected oppositely by pressure gradient. Crossflow is caused by the combination of sweep and pressure gradient. As a result, a large extent of favorable pressure gradient on a swept wing will result in the development of large crossflow velocities in the boundary layer and large crossflow disturbance amplification rates. As shown in Figure 7, the typical optimum pressure distribution for crossflow stability has very large initial pressure gradients near the leading edge of the airfoil, where the boundary layer is thinner and more stable. It then rapidly flattens out, resulting in the decay of crossflow disturbances. On the other hand, the typical optimum pressure distribution for Tollmien-Schlichting stability has large favorable pressure gradients occurring over a large percentage of the chord. The optimum integration of a two-dimensional NLF airfoil into a three-dimensional swept wing airfoil requires shaping the airfoil to have acceptable crossflow stability characteristics at the desired sweep angle, while not allowing the pressure distribution to be compromised from that which is optimum for Tollmien-Schlichting stability. There will be some upper bound on the sweep angle beyond which it will not be possible to stabilize both types of disturbances without making other changes to the wing.

The aircraft trade study identified several areas where further iterations of the NLF airplane could improve the design, such as a thicker wing section at side-of-body; however, the biggest benefit would result from increasing wing sweep as high as possible. The airfoil-wing integration problem and the resulting determination of a realistic upper bound in the allowable sweep angle is one of the most fruitful areas for additional natural laminar flow studies.

RECOMMENDATIONS

1. Additional refinement of the airfoil should be followed by flight test to validate airfoil theory.

2. Parameters affecting requirements of NLF wing design, including wing sweep, thickness, and low speed characteristics, should be evaluated more extensively. This should be followed by investigations toward refined technical and economic analysis based on more optimized design approaches and evaluation of operational problems that NLF would imply.

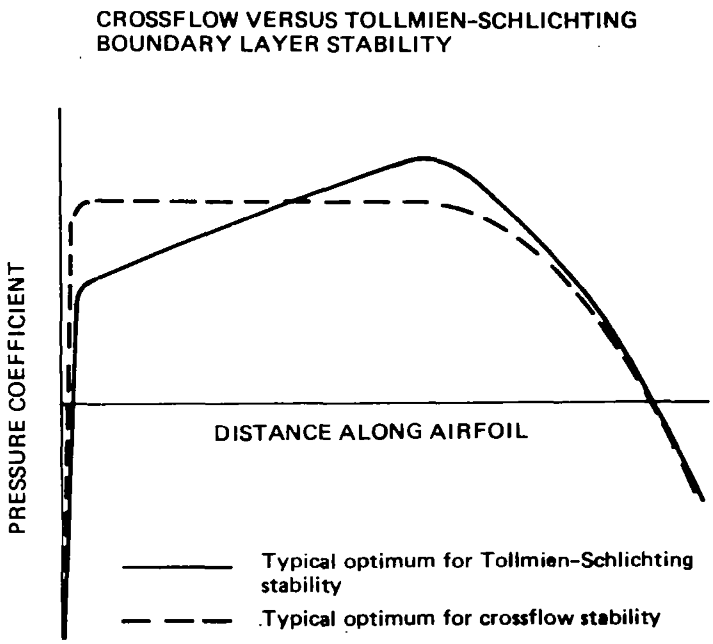


Figure 7. Crossflow Versus Tollmien-Schlichting Boundary Layer Stability

SURFACE COATINGS

OBJECTIVE

Wind tunnel tests conducted by the NASA during 1976 indicated aerodynamic skin friction drag could be reduced with smooth surface coatings applied to wing/empennage surfaces. The objective of work conducted under this contract task was to identify potential coatings that would be durable and provide both drag and erosion reduction under projected operating environments.

APPROACH

Figure 8 indicates the scope of the contract effort and the approach taken under a joint effort by the contractor and the Avco Corporation who performed under subcontract.

An operating environment for a medium-range transport was defined and translated into material and test requirements for candidate materials. Previous work was reviewed, and the large number of available materials was narrowed to 15 liquid coatings, 17 films, and 13 adhesives. Selected coatings and film/adhesive combinations were subjected to screening and more rigorous advanced testing (17 different environmental tests), with 3 liquid coatings and 4 film/adhesives emerging as best candidate materials.

A cost/benefits assessment was made of coatings applied to various areas on a 727-200 airplane, and near-term recommendations were made for future activities. Two of the best coatings were applied to a 727 by Continental Airlines for an extended flight service evaluation.

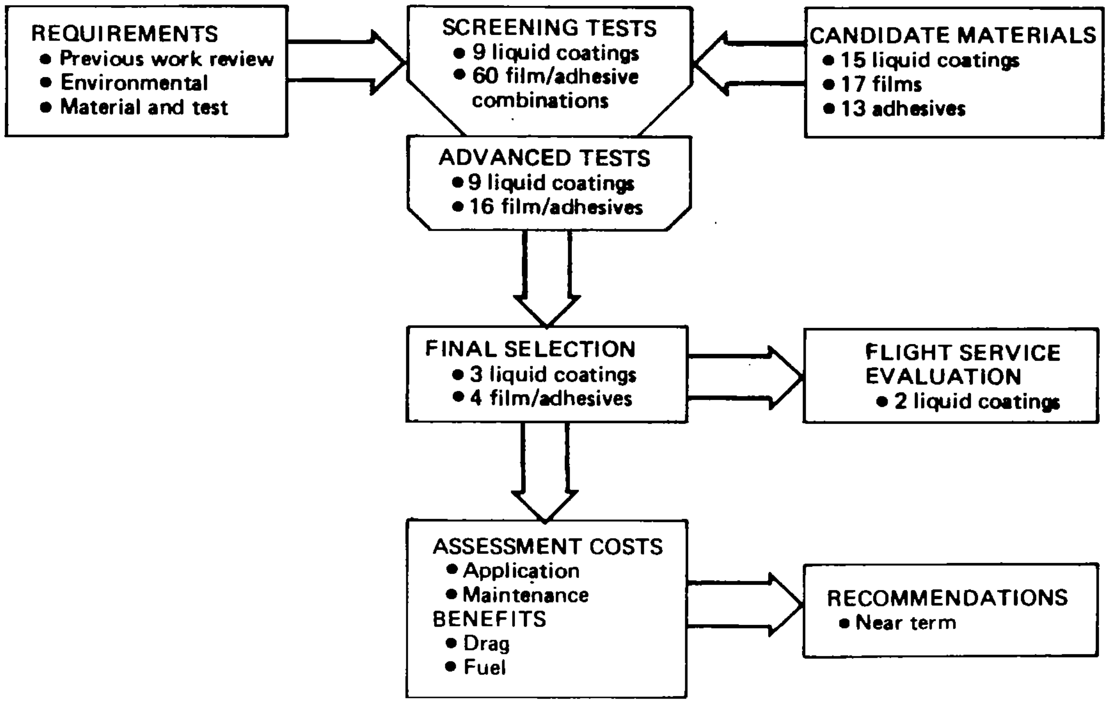


Figure 8. Surface Coatings Evaluation Activities

SURFACE COATINGS
FINAL SELECTED COATINGS TEST RESULTS

Results of critical tests conducted on the seven final selected coating and film concepts are shown in Table 1. These environmental tests showed generally satisfactory characteristics. The liquid coatings, however, dissolved after extended submersion in Skydrol-type hydraulic fluid. Of the film/adhesive concepts, Tradlon/PR1422 was the only one unaffected by extended submersion in Jet-A fuel. It exhibited reduced adhesion, however, after the 62-day salt spray test.

Rain erosion results were converted to equivalent transport operating hours by Springer's method. The liquid coatings had a predicted life of between 2000-6000 hours, whereas the best film/adhesive concepts (Tradlon, UHMW Polyolefin) had a predicted life of only 117 hours.

Of the liquid coatings, only Astrocoat requires a controlled atmosphere (humidity and temperature) for spray-on application. CAAPCO and Chemglaze can be applied under ambient conditions (recommended temperature, 21°C (70°F). A feasible method of applying films to large areas, especially those with compound curvature, could not be devised. It is essential that this problem be solved before serious consideration can be given to film applications on a fleet-wide basis.

Table 1. Final Selected Coatings Test Results

Selected concepts	Environmental tests satisfactory except:	Predicted rain erosion life (flight hours)	Application comments
Liquid coatings (polyurethane)			
CAAPCO B-274	Not compatible with extended exposure to Skydrol-type hydraulic fluid	5880	Feasible
Chemglaze M313		2925	Feasible
Astrocoat		1828	Controlled atmosphere
Film/adhesive			
Tradlon/PR 1422	Reduced adhesion in salt spray	Not suitable for high erosion areas	Application to large areas currently not feasible
Kapton/PR 1422	Affected by Jet-A		
UHMW Polyolefin (A/B)	Bond failure in Jet-A		
Kynar/adhesive 80	Bond failure in Jet-A		

SURFACE COATINGS
COST/BENEFITS

Application and maintenance costs of the three liquid coatings, over those for normal painting, were estimated for various amounts of surface coverage, as shown for Cases I, II and III in Figure 9. Drag reduction from the coatings was calculated by assuming that drag due to surface roughness would be eliminated, and the drag due to excrescences would be reduced. These reductions in drag were termed potential drag reduction. The estimated maximum potential reduction for Case I is approximately 0.17% of 727-200 cruise drag; that for Case III is about 1.62%.

Benefits gained from reduced fuel consumption (reduced drag) are shown on Figure 9 as a function of fuel price and as a function of percent of the potential drag reduction. Drag measurement tests are necessary to establish the actual drag benefits from the coatings.

It was estimated that CAAPCO B-274, applied from the leading edge to the rear spar on the wing and empennage of a 727-200, could reduce annual fuel consumption by as much as 34 000 gal, if 100% of the potential drag reduction were realized. Assuming fuel at 40 cents/gal, this would result in a net operating cost reduction of about $8600/yr for each airplane in the fleet. The airline would break even if only 1/3 of the potential drag reduction were realized. Cost reduction, due to reduced maintenance resulting from decreased leading-edge erosion, would be additive to the benefits shown.

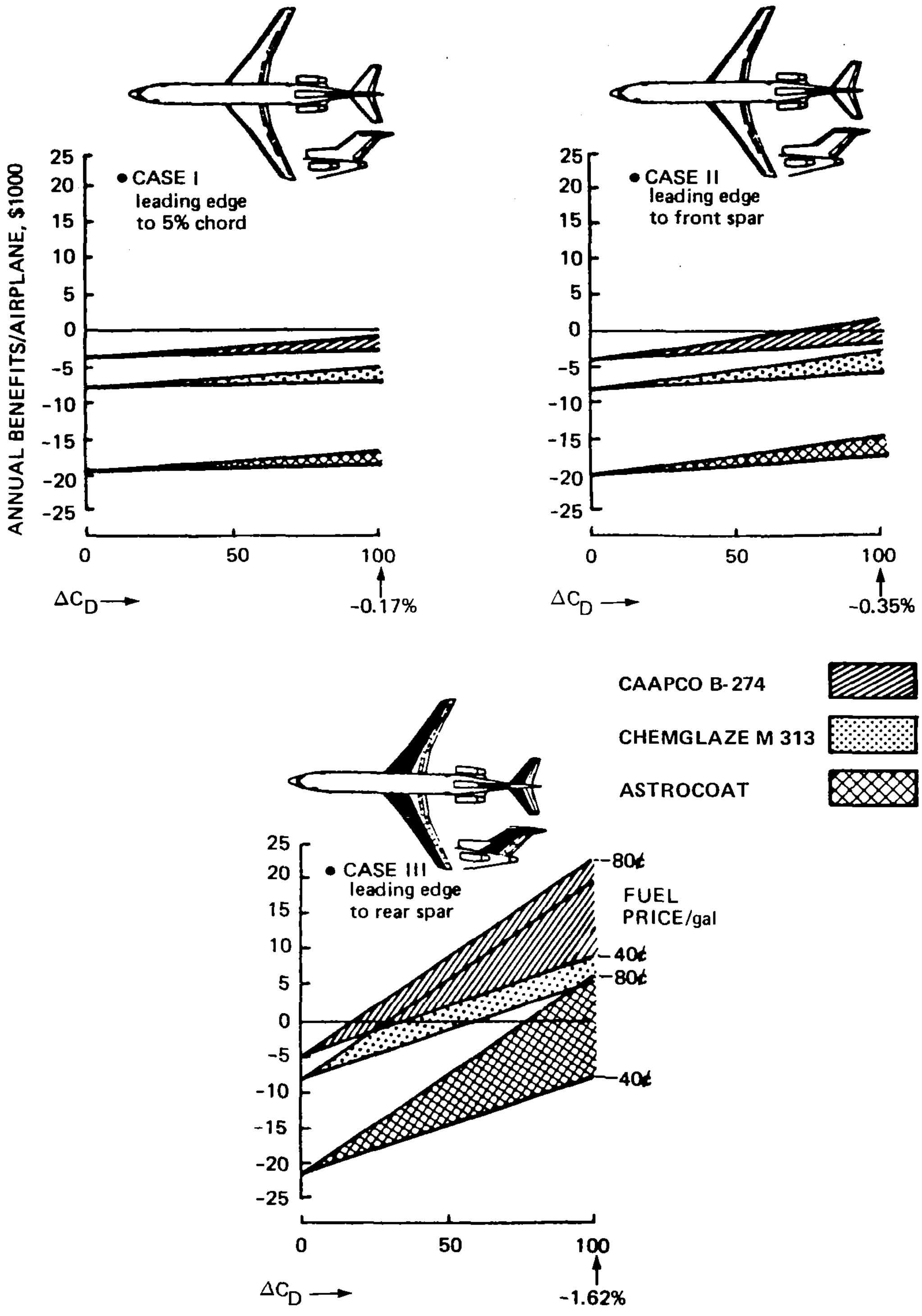


Figure 9. Surface Coatings Potential Economic Payoff

SURFACE COATINGS
FLIGHT SERVICE EVALUATION

EVALUATION

A flight service evaluation of the two coating candidates showing good potential was begun on 15 September 1978. As shown in Figure 10, CAAPCO B-274 and Chemglaze M313 were applied to left- and right-hand leading-edge surfaces, respecitively, of an Air Micronesia 727. The materials were sprayed on the airplane by Continental Airlines maintenance personnel who had no previous experience with these coatings. No special facilities or equipment were required. The materials are under observation for a 1-year period and their condition reported periodically. Since application in September 1978, reports from Continental Airlines have been very encouraging after nearly 2000 flight hours and over 1500 landings in a high erosion environment.

CONCLUSIONS

Any of the three liquid coating or four film/adhesive final concepts applied to the wing and empennage back to the rear spar could reduce 727-200 airplane drag by as much as 1.6%. Coatings or films meet an adopted smoothness criterion of 2 mils (taken as a nominal roughness necessary to trip laminar flow). However, there is no known process that is economically feasible for applying films over large curved surfaces.

Additional data are needed to identify drag benefits from coatings, to better define application and maintenance costs, and to determine the durability of coatings in an airline environment.

RECOMMENDATIONS

Results of the study indicate that smooth coatings should be emphasized in future work. Additional research is required to develop application, repair and maintenance procedures on large-scale surfaces. Measurement of the drag reduction they can yield should be conducted in the form of flight and/or wind tunnel testing.

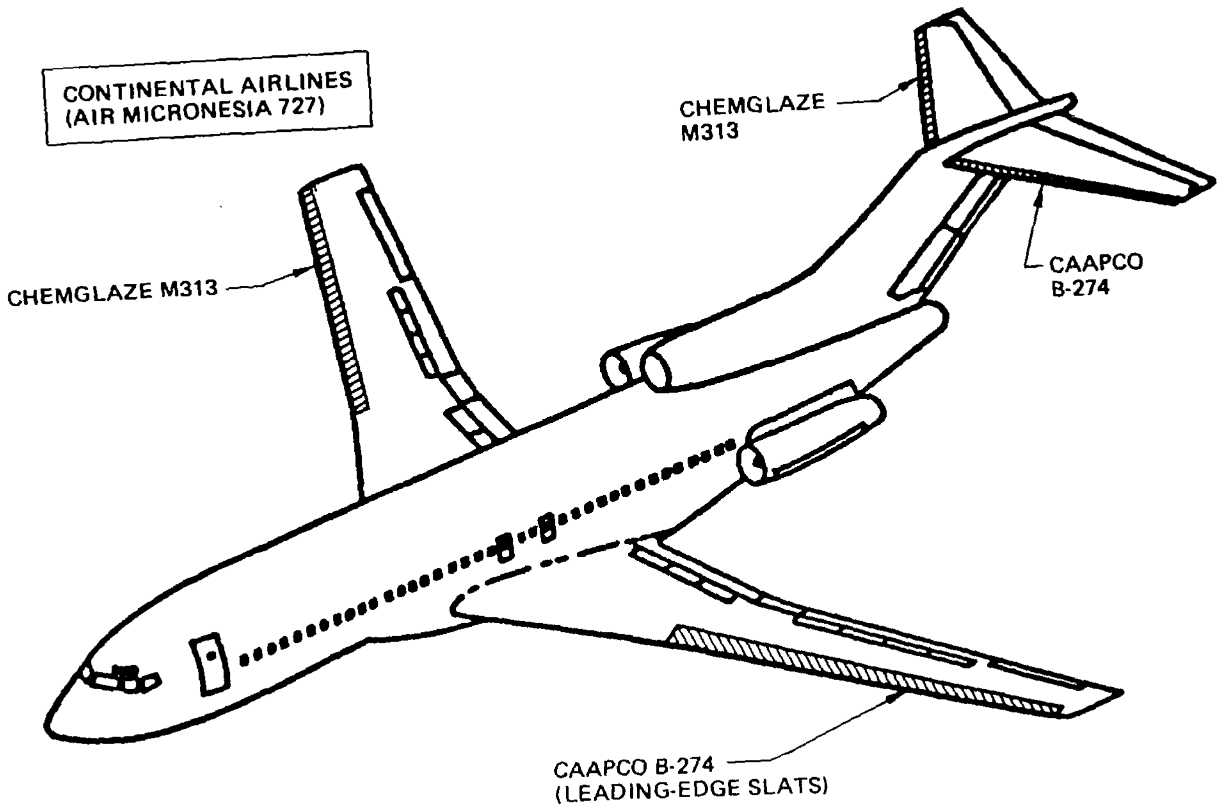


Figure 10. Surface Coatings in Service Evaluation

HIGH LIFT CONCEPTS

OBJECTIVES

Pre-contract, theoretical investigations funded by the contractor had resulted in definition of analytical techniques for design and prediction of high lift airfoil performance at high Reynolds numbers. The broad objectives of the task subsequently pursued under this contract were:

- Design Application Studies: Demonstrate and determine the benefits to high-lift system maximum lift and, alternatively, to high-lift system complexity, of applying the newly-developed analytical design and analysis techniques to the design of high-lift sections for flight conditions.
- Requirements Definition Studies: Clarify the influence of the high-lift system on the sizing and economics of an energy efficient transport (EET).
- Impact Study: Evaluate the impact of the best design resulting from the design application studies on EET sizing and economics.

THEORY APPLICATION DEMONSTRATION

To gage the quality of the analytical design work, the theoretical lift curve of a representative high-lift system, predicted by a Boeing computer program using separated flow theory, was compared with existing wind tunnel data. In this comparison, $C_{\ell_{max}}$ was predicted within 2%. The angle of attack for $C_{\ell_{max}}$ and C_ℓ at low angles of attack were predicted even more correctly. Figure 11 displays these results.

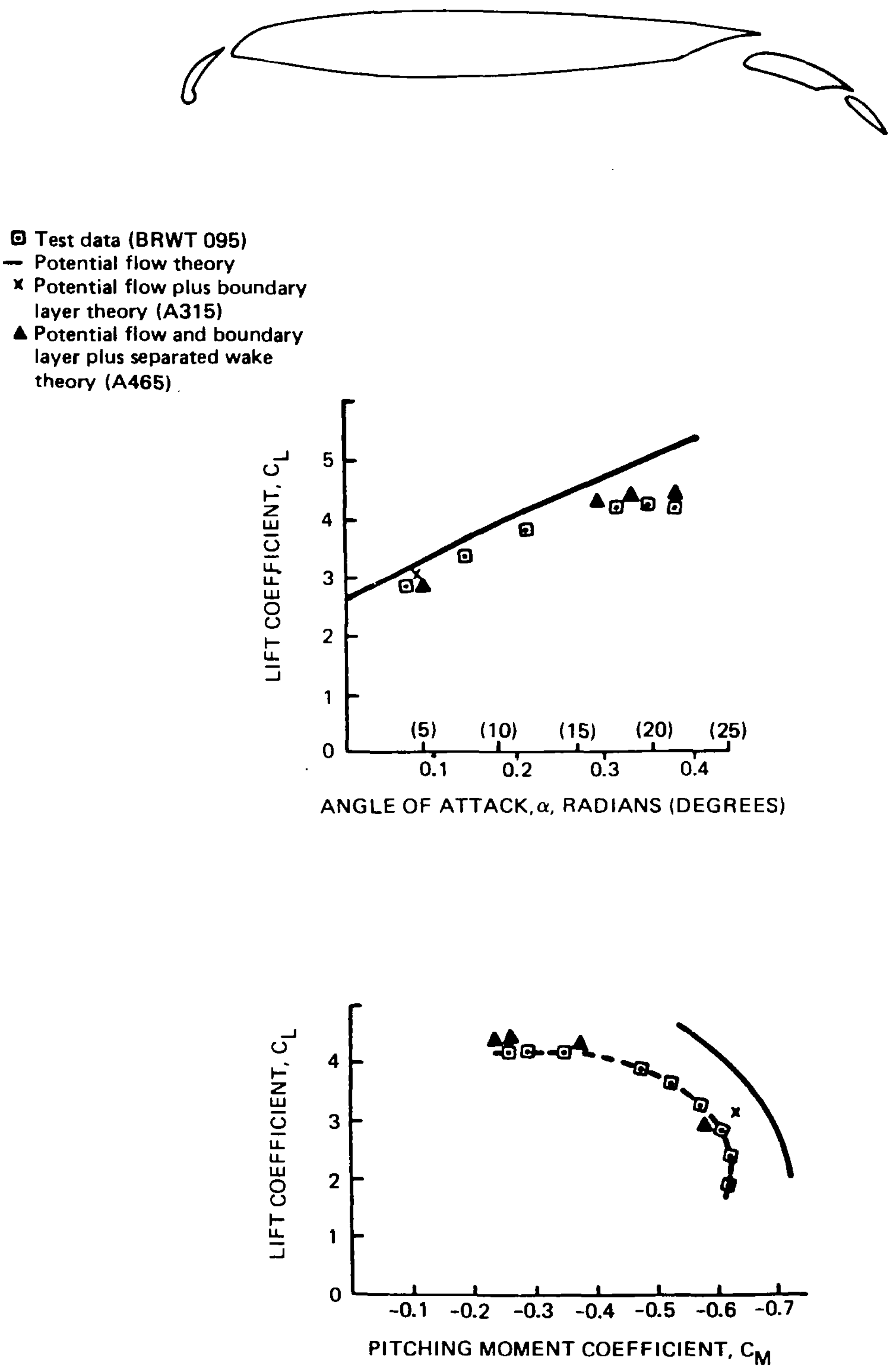


Figure 11. Comparison of Theory and Test

HIGH LIFT CONCEPTS
AIRFOIL DESIGN APPLICATIONS

The analytical technique developed in the study was evaluated by designing a four-element high-lift airfoil at flight Reynolds number (17×10^6) and comparing it to a similar airfoil designed by conventional low Reynolds number (2×10^6) techniques. At flight Reynolds number, a 13% improvement in $C_{\ell_{max}}$ resulted for the high Reynolds number design. Theoretical lift curves of the two airfoils are shown in Figure 12, which also compares section geometries.

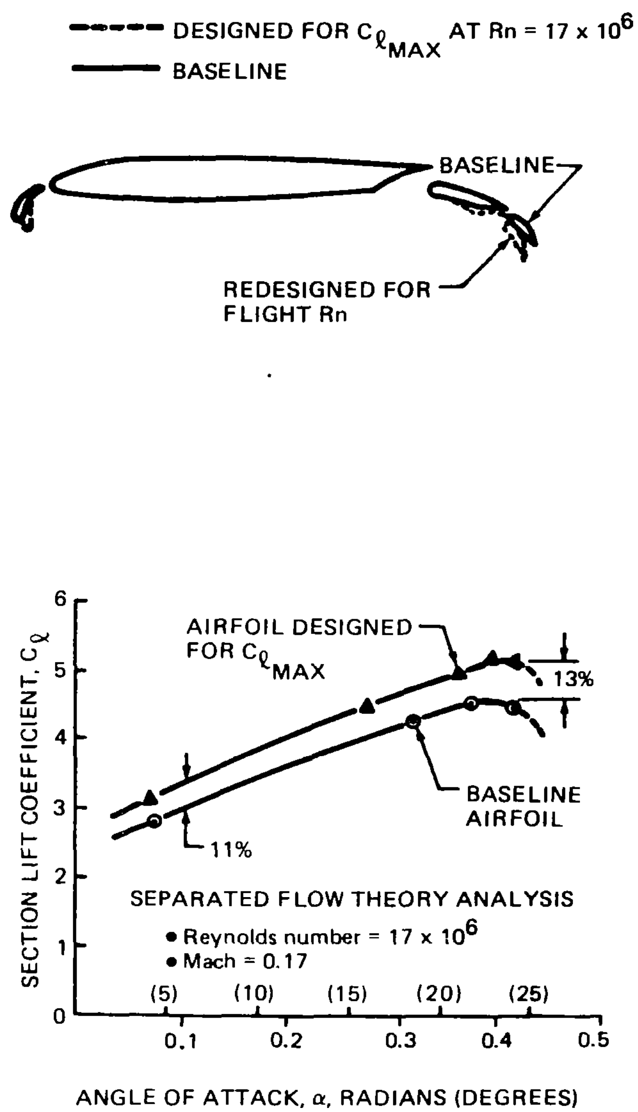


Figure 12. High-Lift Airfoil Improvement Through Theory Application

HIGH LIFT CONCEPTS
SIMPLIFIED DESIGN APPLICATION

As a further application, a three-element, simplified airfoil, was designed at flight Reynolds number to produce the same $C_{\ell_{max}}$ as the conventional four-element section. The theoretical lift curves and geometries of these two sections are compared in Figure 13.

An important by-product of these design tasks was the validation of a rational design method for the synthesis of multielement high-lift airfoils. Using analytic techniques, this methodology allows optimization of pressure distributions and airfoil shapes within the aerodynamic and structural constraints, and eliminates the trial-and-error design process. This methodology represents a significant improvement in high-lift system design techniques.

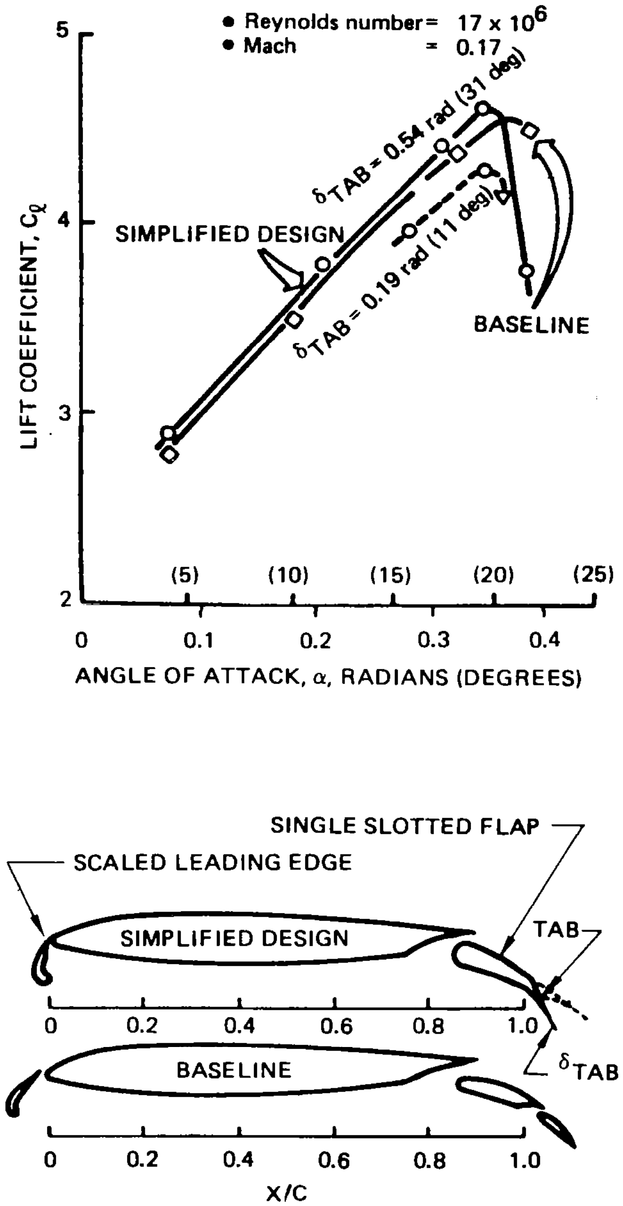


Figure 13. Three- Versus Four-Element Airfoil Performance

HIGH LIFT CONCEPTS REQUIREMENT DEFINITION

To evaluate the benefits offered by the refined high lift concepts, an advanced-technology, twin-engine transport configuration was selected as the baseline for the sizing trade studies. This configuration is illustrated in Figure 14. In fixed-mission sizing studies, the baseline airplane was found to be insensitive to landing $C_{\ell_{max}}$ improvements due to the low wing loading required to satisfy sea level takeoff and enroute engine-out altitude requirements. Its performance was found to be most sensitive to improvements in takeoff lift-to-drag ratio (L/D), particularly at low lift coefficient levels typical of takeoff out of high, hot airports (e.g., Denver).

Selection of an airplane design for minimum energy consumption conflicts with selection of an airplane design for minimum airplane takeoff gross weight for the 196-passenger, 3704-km (2,000-nmi) mission requirements assumed in the trade studies. The design selection chart shown in Figure 15 reflects the following study results:

- Disregarding restraints imposed by takeoff, landing, and engine-out altitude, selection of an airplane design for minimum energy consumption produced an 8.5% increase in takeoff gross weight relative to the minimum gross weight design.

- Similarly, selection of an airplane design for minimum takeoff gross weight produced a 7% increase in energy consumption for the design mission relative to the minimum energy design.

- The baseline airplane which was selected to have minimum takeoff weight and to just satisfy the 2286-m (7500-ft) sea-level takeoff requirement, has an 0.5% increase in energy comsumption and a 3.5% increase in takeoff weight relative to the two design minimums.

CONCLUSIONS AND RECOMMENDATIONS

The "simplified" high-lift section produced in the design application studies most closely matched the requirements of the baseline configuration. This airfoil section was used because $C_{\ell_{max}}$ was not increased and the improved design techniques were directed toward simplifying the section and increasing L/D. Application to the baseline configuration resulted in a 13% (26 passenger) increase in payload out of Denver relative to the baseline configuration. The improvment in L/D (5.6% at takeoff lift levels) achieved by using this section did not permit wing resizing because the engine-out altitude requirement of 3658m (12,000 ft) would be violated at the higher wing loadings of the resized wings. Therefore, a reduction in airplane size did not result. If sized for minimum direct operating cost (DOC) for the high-altitude, hot-day mission, use of the "simplified" flap would result in a 6% reduction in DOC relative to the resized baseline.

Follow-on work should be conducted separate from Phase II contract work. It should concentrate on the design of a high-lift section that would improve L/D performance at low lift coefficients typical of the Denver takeoff. It is recommended that a section designed for takeoff L/D, and the section designed for improved $C_{\ell_{max}}$ during this contract be tested in the NASA/Langley Research Center Low-Turbulence Pressure Tunnel.

- Payload — 196 passengers
- Range — 3704 km (2000 nmi)
- TOGW — 124 230 kg (273 300 lb)
- Body diameter — 5.4m (212 in)
- Wing area — 236 m^2 (2535 ft^2)
- Aspect ratio — 10.24
- Sweep — 0.52 rad (30 deg)
- Engines (2) — CF6-50C (scaled)
- SLST — 164 kN (36 930 lb)

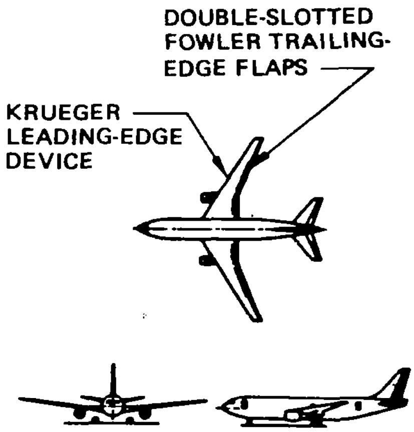


Figure 14. Baseline Configuration

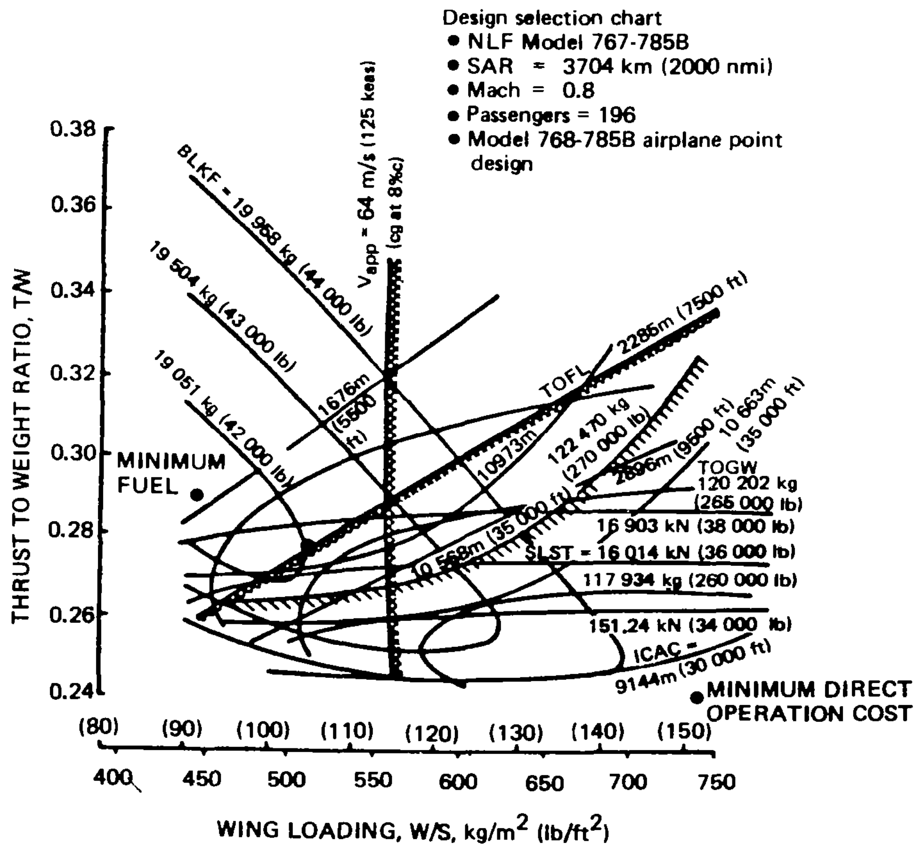


Figure 15. Configuration Selection

INTEGRATED ENERGY MANAGEMENT (IEM)

The Integrated Energy Management (IEM) Study established the feasibility, practicality, and potential benefits of a system that would furnish direct control (with manual override) of autothrottle and autopilot functions to yield minimum energy flight profiles. The direct control features differ from current advanced systems that provide flight advisory information to the crew, with subsequent manual control.

OBJECTIVE

The specific objective was to develop primary guidance and control algorithms for a candidate system, and evaluate the potential fuel savings it would offer.

APPROACH

The approach taken in the development of energy management algorithms and their assessment is summarized in Figure 16. The first study area comprised an analysis of medium-range transport operations. This analysis was based on data taken in an in-flight measurement program of a specially instrumented 727-200, flying revenue passenger routes in airline operations. United Airlines cooperated in this part of the study. Eighty scheduled flights, operating over 43 city pairs were evaluated. Two flights were selected, representing typical medium-range and short-range routes. Data extracted from these flights were used to recreate the flight conditions in a computer simulation model. Implementation of the energy management algorithms in the model and assessment of the benefits concluded the study tasks.

The model was employed in the study in two modes: recreating selected flight conditions to establish a performance base against which to measure energy management algorithm benefits, and employing the guidance logic. The development of energy guidance algorithms was based on an analysis of alternative approaches to the establishment of fuel-efficient procedures. The alternatives were compared in terms of fuel and time efficiency, and in terms of their compatibility with objectives. Climb, cruise, and descent factors and constraints were analyzed. The selected technique - specific energy optimization - forms the basis for the algorithm mechanization logic developed. Algorithms for climb, cruise, and descent were detailed, and associated sensor requirements were specified.

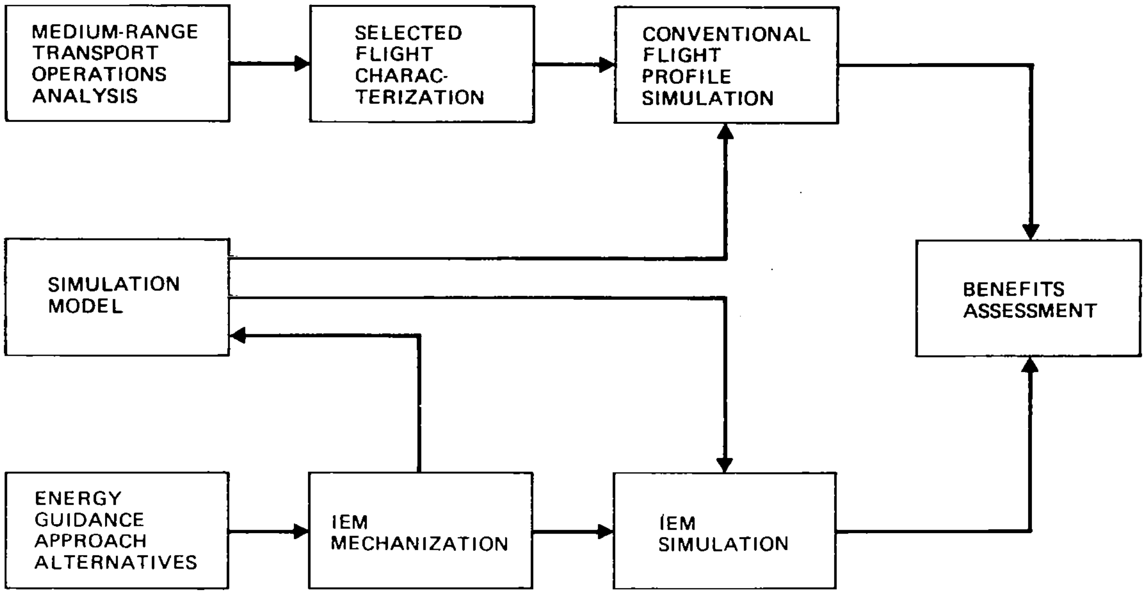


Figure 16. Algorithm Development Activities

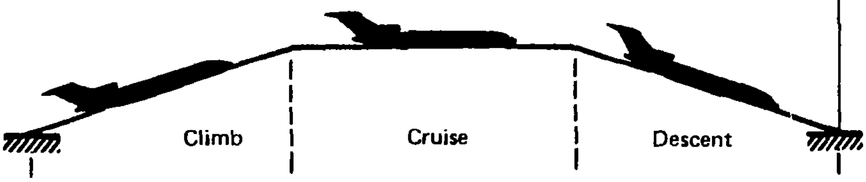
INTEGRATED ENERGY MANAGEMENT (IEM)
FINAL CONCEPT

As indicated in Table 2, the selected energy guidance technique uses the concept of specific energy (the sum of the aircraft kinetic and potential energies divided by the aircraft weight). Climb strategy was to maximize rate of change of specific energy per unit fuel flow to a fixed range. Cruise strategy was to maximize specific range. Descent strategy was to minimize rate of change of energy per unit fuel flow, again to a fixed range.

The concept of an on-board sensed, closed-loop optimization technique for climb and descent was determined infeasible without reference to stored performance data. Mechanization of the guidance algorithms for climb and descent requried stored performance values of thrust, drag, and fuel flow. The mechanized climb and descent algorithms were combined with engine pressure ratio-hold autothrottle mode and an airspeed-hold autopilot mode to automatically control attitude and thrust in climb and descent. The closed-loop on-board sensed mechanization for cruise control was investigated and determined feasible. An initial cruise algorithm used in conjunction with an airspeed-hold autothrottle mode was developed. The cruise algorithm samples specific range values, using measured velocity, acceleration, and fuel flow data. When an optimum is located, an error signal is generated for the autothrottle. The algorithm monitors speed, weight, and fuel flow data. When required, a new search or acquire mode is initiated.

Table 2. Final Algorithm Characteristics

E_s = specific energy
W_f = pounds fuel



	Climb	Cruise	Descent
Guidance	Maximum $\frac{d\,E_s}{d\,W_f}$	Maximize Specific range	Minimize $\frac{d\,E_s}{d\,W_f}$
Input data			
Stored	• Thrust, drag, and fuel flow	————	• Thrust, drag, and fuel flow
Onboard sensed	————	• Speed—air and ground • Acceleration • Fuel flow	————
Autopilot mode	IAS hold	Altitude hold	IAS hold
Autothrottle mode	Maximum climb EPR schedule	Airspeed hold	Idle EPR schedule

INTEGRATED ENERGY MANAGEMENT (IEM) EVALUATION

BENEFITS ASSESSMENT

The benefits assessment was conducted using current 727-200 operational equipment and performance with conventional flight procedures as the comparison baseline. Results are shown in Table 3. Fuel saving potentials were found for the three flight segments of the 1098.6 km (593.1 nmi) selected flight example mission. A 5.0% fuel reduction for that flight resulted. Trip time increased aproximately 12%, largely due to the fuel optimum speed/thrust schedules that would apply throughout the flight profile.

CONCLUSIONS

Although it was necessary to modify the initial concept by using on-board stored (rather than sensed) data during the climb and descent segments, an attractive fuel savings using a feasible and practical closed-loop system, was established. When applied to all of the 80 recorded flights used for the study, a 4.8% fuel reduction with increased time was estimated. The savings would be less if compared with systems that provide data to the flight crew with subsequent manual control. In this respect, however, the concept would reduce crew workload, while providing for crew override.

Application of the concept will be a function of the relative economic advantage it will offer in the future, considering fuel availability and cost, and trip time. These factors will in turn be affected by individual airline route structure and operational procedures.

RECOMMENDATIONS

The study provided the basis for industry to proceed with implemetnation of the IEM concept for airlines whose route structure and fuel cost/availability environment make the concept attractive. No further contract effort is needed.

Table 3. Final Algorithm—Fuel Use and Trip Time

	217.8 km (117.6 nmi)	717.8 km (387.6 nmi)	163 km (88 nmi)	Total 1098.6 km (593.1 nmi)
Trip fuel, kg (lb)				
• Conventional	1633 (3601)	2872 (6333)	371 (817)	4876 (10751)
• IEM	1544 (3404)	2790 (6153)	298 (656)	4632 (10213)
△	89 (-197) (-5.5%)	82 (-180) (-2.8%)	73 (-161) (-19.7%)	244 (-538) (-5.0%)
Trip time, min				
• Conventional	16.10	49.85	12.15	78.10
• IEM	17.02	54.57	16.10	87.68
△	+0.92	+4.72	+3.95	+9.58 (+12.3%)

INTEGRATED APPLICATION OF ACTIVE CONTROLS (IAAC)
(MAXIMUM BENEFIT OF ACTIVE CONTROLS)

OBJECTIVE

The objectives of this task were to evaluate major application of active controls technology to commercial transport design; to determine the overall research program plan that should be followed to permit such application, and to initiate action on the early part of the plan.

APPROACH

A qualified management and technical team was assembled that included representatives of all technical disciplines affected by ACT application. The team was assigned initially to establish the conditions under which maximum benefit of ACT could be expected to accrue. Subsequent investigations were directed toward definition of the steps that should be taken to more adequately define the potential benefits of ACT and to pursue necessary development. Key findings are listed below.

- Maximum potential will be realized by applications of ACT during the preliminary design process rather than adding it to existing transport designs.
- Design criteria applicable to commercial transport ACT have not been developed.
- Although gross estimates of the potential have been made based on assumed design criteria, no record of a credible assessment was found.
- A three element program (shown in fig. 17) was defined as a basis for:

  Element 1: Configuration Design and Development
  - Development of proper design criteria applicable to an ACT transport.
  - Determination of the magnitude of ACT potential as a measure of the desirability of proceeding with development.
  - Identification of the specific developmental research that should be pursued.

  Element 2: Advanced Control System Studies
  - Identification of control system technology advancements that could provide reliability and cost of ownership improvement.
  - Definition of the interrelationships between ACT and other (navigation, guidance, displays, etc.) systems.

  Element 3: ACT Systems Development
  - Verification of ACT airplane potential.
  - Establishment of confidence in ACT systems through appropriate test and development.

The results were identified as the Integrated Application of Active Controls (IAAC) Program Plan. Portions of the long range plan initiated during the Phase I contract were to continue during Phase II under the IAAC acronym, and are so referred to hereafter.

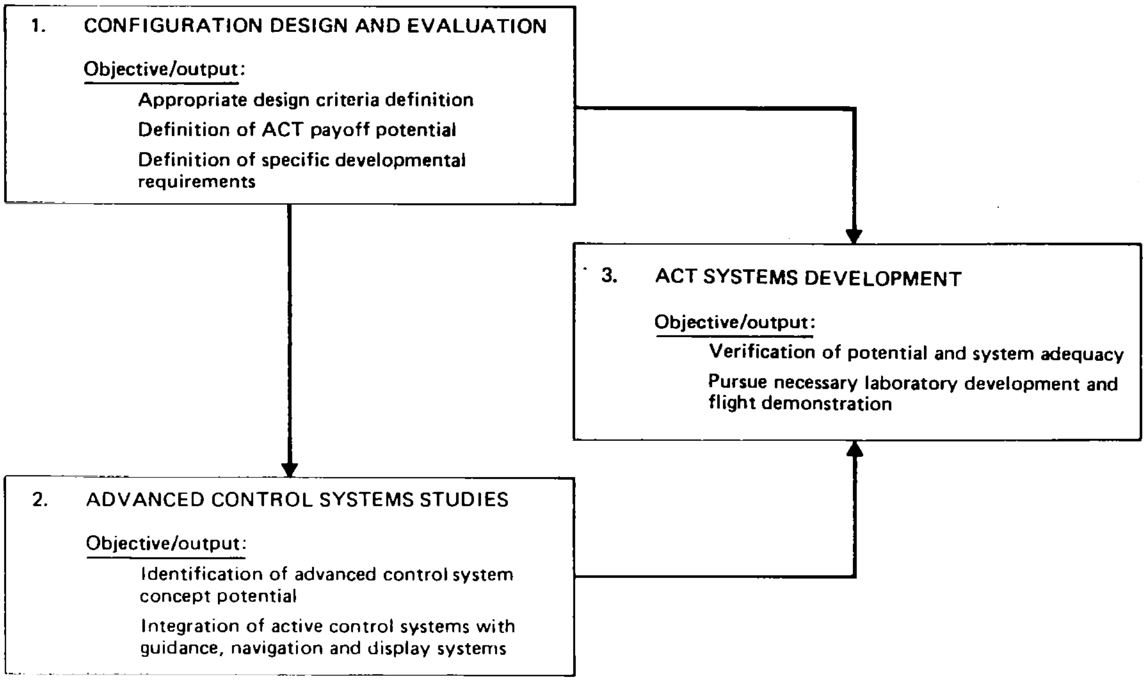


Figure 17. Program Plan Elements

INTEGRATED APPLICATION OF ACTIVE CONTROLS (IAAC) CONFIGURATION DESIGN AND EVALUATION ELEMENT

Early in the Phase I work, it became clear that the following two questions must be answered before major ACT development should proceed.

1. What is the real benefit potential for active controls when applied to commercial transport designs considering their impact on structural, aerodynamic, and overall configuration design - and is that potential sufficiently great to warrant extensive ACT development?

2. What specific developments are required to realize the full potential.

The configuration design and evaluation element, consisting of the activities shown in Figure 18, is postured to provide answers to these questions. The purpose of each activity is described below:

- Design Requirements and Objectives (DRO) -
  Document definition of the design criteria for all technical disciplines for a commercial transport to rely on active controls for load alleviation, flutter suppression and stability augmentation.

- Conventional Baseline Configuration -
  Detail definition of a conventional (non-ACT) airplane for use as a base for ACT payoff measurement.

- Initial ACT Configuration -
  Definition of a configuration having the same wing planform as the conventional baseline configuration but that utilizes ACT to provide reduced stability and reduced wing structure design loading.

- Wing Planform Studies -
  Determine wing characteristics (aspect ratio, sweep, and thickness) with best potential for an ACT airplane.

- Final ACT Configuration -
  Detailed definition of a configuration sized for the same mission requirements as the conventional baseline configuration that takes best advantage of ACT.

- Evaluation -
  Comparison of the technical and economic performance of the final configuration with those of the conventional baseline configuration as a credible measure of ACT potential.

- ACT Control System Definition -
  A preliminary control system definition, development of an ACT system technology base (current technology) and the specification of an ACT control system for the Final ACT Configuration that meets defined dispatch and reliability rquirements.

Available Phase I funding permitted completion of the Conventional Baseline Configuration and the initial DRO, as well as the start of the Initial ACT Configuration and Control System Definition studies. The remainder of this report summarizes key findings in those areas. The remaining activities are expected to proceed during Phase II. Throughout the Configuration Design and Evaluation element activities, control system definition will be based on state-of-the-art design approaches. This will permit final decisions to be made without reliance on a technical breakthrough. Advanced system concepts will be examined during Phase II for possible inclusion in the evaluation update.

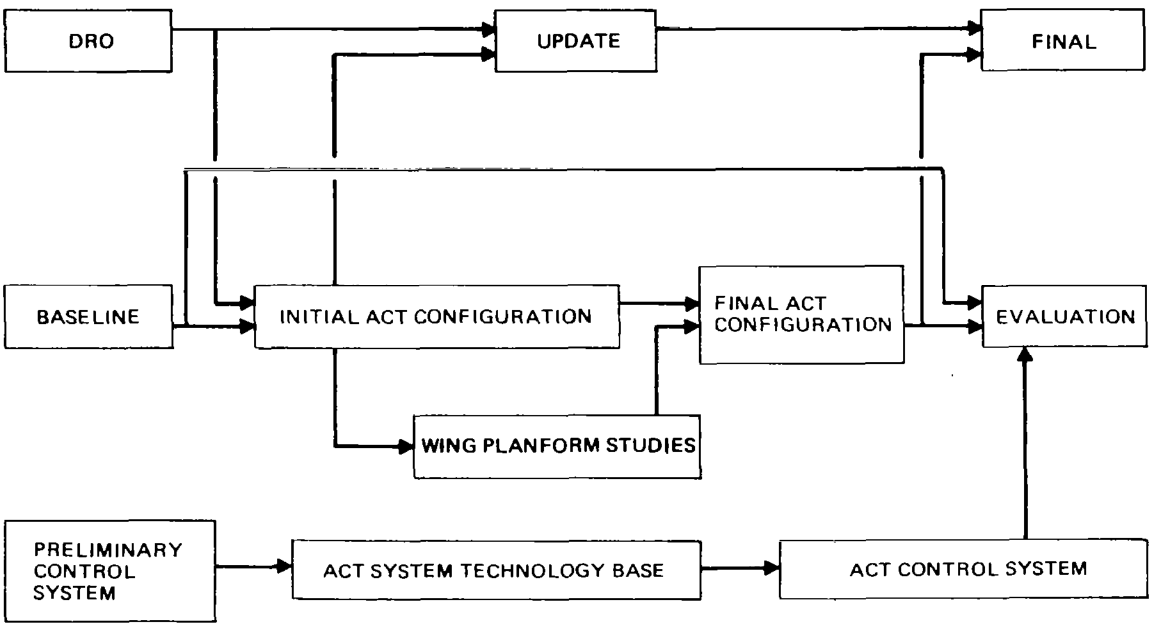


Figure 18. Configuration Design and Evaluation Element

INTEGRATED APPLICATION OF ACTIVE CONTROLS (IAAC) DESIGN CRITERIA

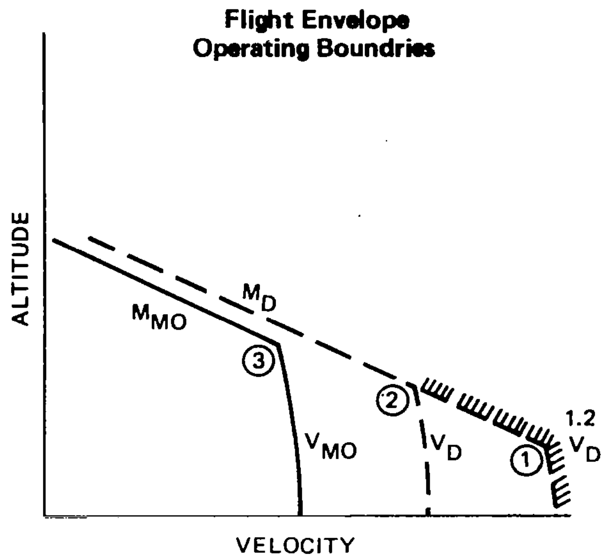
The overall strategy of the IAAC study is to identify the benefits of active control functions by carefully including only changes due to active controls, while retaining non-active control characteristics of the baseline configuration. For instance, the ACT configurations should not be quieter than the baseline if such improved noise characteristic costs anything in performance. A significant foundation block for a complete study is the identification of the design requirements and objectives (DRO) for the baseline, and development of an understanding of what aspects of that DRO must be changed to allow incorporation of active controls. The development of design requirements and objectivs has shown that the bulk of the DRO for a conventional airplane will apply with little or no modifications to an active control airplane.

One exception is flying qualities criterion. A conventional airplane will typically exhibit safe, if not satisfactory, characteristics following the failure (loss of function) of certain of its augmentation systems or automatic controls. In contrast, an active control airplane that has been designed to be dependent upon augmentation will experience degraded, if not unsafe characteristics, if that augmentation ever totally fails.

An example of the impact of ACT on structural criteria is shown by the diagram and table in Figure 19. The table lists three flight conditions, the boundaries of which are described by the figure as a function of flight velocity (V) and Mach (M) number as they vary with altitude.

The current flutter criteria for conventional airplanes shown by the left-hand column of the table, require that the airplane shall be shown to be flutter free, by analysis and model tests, to a speed 20% beyond the dive placard, i.e., 1.2 V_D (bounded by the shaded line noted as 1 on the diagram). After the airplane has been built, the airplane must be shown through flight test to be free of flutter to the dive placard, i.e., V_D (bounded by the dashed line noted as 2 on the diagram).

The proposed criteria for an airplane that uses a flutter mode control system are shown in the right-hand column of the table. These criteria would require that the airplane with flutter mode control inoperative must be shown by flight test to be flutter free within the V_{MO}/M_{MO} boundary (identified by the solid line noted as 3 on the diagram). With the flutter mode control system operative, the airplane would be shown through flight test to be flutter free to V_D (boundary 2). During design of the airplane, it would be shown by analysis and model test to be flutter free to V_D (boundary 2) with the flutter mode control (FMC) system inoperative. Finally, the airplane would be shown by analysis and model test to be flutter free to the 1.2 V_D placard (boundary 1) with the FMC operational.



Criteria

Airplane shall be free from flutter in accordance to:

	Current criteria for conventional airplanes	Proposed criteria for airplane with flutter mode control
①	By analysis and model test to 1.2 V_D	By analysis and model test with FMC on to 1.2 V_D
②	By flight test to V_D	By analysis and model test to V_D FMC OFF By flight test to V_{MO} with FMC ON
③		By flight test to V_{MO} with FMC OFF

Figure 19. Structural Placards—Current and Proposed With Flutter Mode Control

INTEGRATED APPLICATION OF ACTIVE CONTROLS CONFIGURATION CHARACTERISTICS STATUS

The configuration design and evaluation activities are focused on configurations suitable for medium-range missions since such missions constitute a major share of domestic airline operations and, thereby, high total fuel usage. Specifically, the conventional baseline is designed to a 197 passenger, 3704km (2000 nmi) design range mission requirement. A two-engine, seven-abreast seating configuration was selected for the baseline because of an available large analytical and wind tunnel test data base. The DRO for that configuration was evaluated and modified as appropriate to take into account the expected impact of ACT.

Figure 20 shows the outline geometry of the Conventional Baseline Configuration. The geometry of the Initial ACT Configuration, as it appeared at the completion of this Phase I contract, is also shown by the cross-hatched area. The Initial ACT Configuration was constrained by the following ground rules that were applied during this portion of the task:

- Takeoff gross weight, propulsion system, wing planform area and spar locations, and empennage planform to remain the same as the baseline configuration.
- All beneficial ACT functions are assumed to be available.
- Operational and passenger/cargo flexibility of the baseline configuration to be retained.
- Wing movement relative to baseline configuration to be multiple of frame spacing and/or standard cargo containers.

Relative to the Conventional Baseline, the Initial ACT Configuration differs in the following major points:

- Wing moved 1.68m (66 inches) forward on body.
- Horizontal tail area reduced 45%: 25.64 m^2 (276 ft^2).
- Center of gravity range reduced $3\%c_W$ and shifted aft (relative to wing) $9.5\%c_W$.
- Main gear center of rotation moved aft $8.9\%c_W$.
- Vertical tail area reduced 6%: 3.44 m^2 (37 ft^2).

At the end of the Phase I contract, partial completion of the Initial ACT Configuration indicated that it offered the potential of an approximate 15% increase in mission range at the same takeoff gross weight as the Conventional Baseline. Final definition of the Initial ACT Configuration and completion of the remaining Configuration Design and Evaluation activities are planned to occur during Phase II.

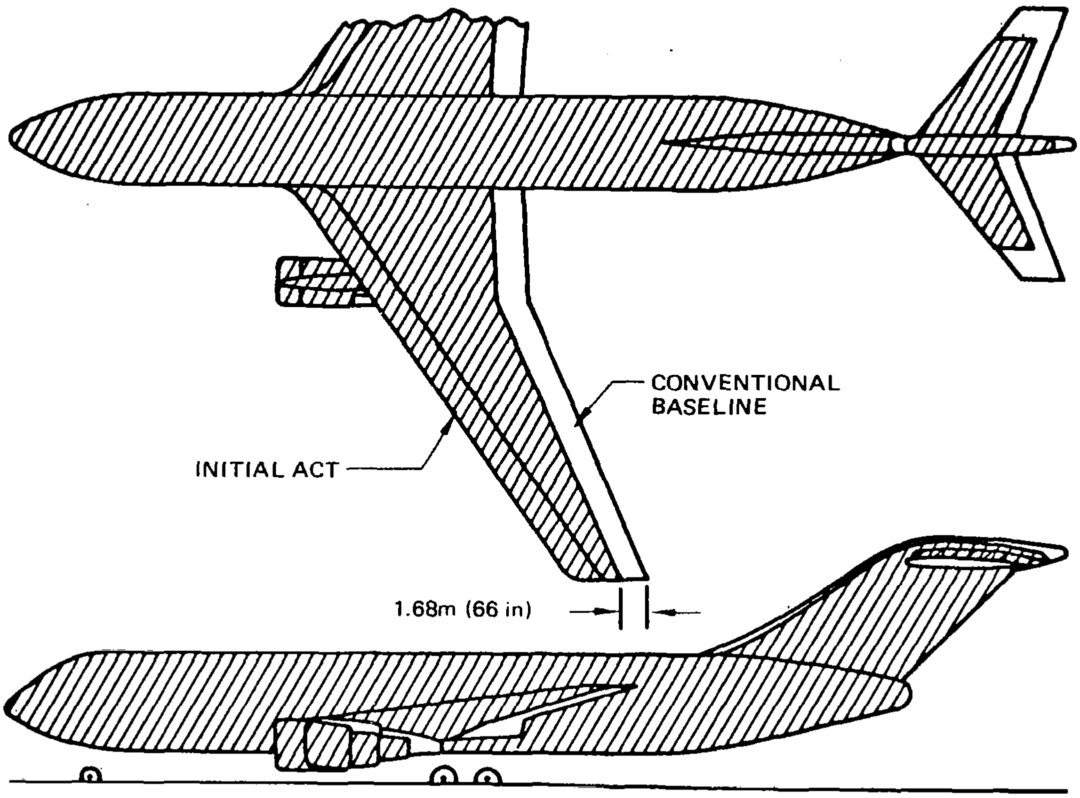


Figure 20. Baseline and Initial ACT Configurations—Comparison

747 PRIMARY FLIGHT CONTROL SYSTEMS RELIABILITY AND MAINTENANCE STUDY

OBJECTIVE

The objective of this task was to develop a baseline for evaluation of the reliability and maintenance characteristics of advanced flight control systems based on historical records of the contemporary systems and components used on the model 747.

APPROACH

As shown in Figure 21, the reliability analysis was performed using a computer-aided redundant system reliability analysis (CARSRA) program previously developed for NASA by The Boeing Company.

To support the reliability analysis, component failure rates were generated from airline unscheduled component removal histories and workshop findings. System modeling, using a Markov model approach, was developed from functional diagrams of each control system.

For the maintenance cost assessment, airline maintenance manhours, material costs, and delay and cancellation rates were collected at the component level. Costs for 1978 were generated from labor rates and industry estimates of delay-time costs.

The systems included in the study were:

- Rudder Control
- Stabilizer Control
- Elevator Control
- Lateral Control
- Speed Brakes

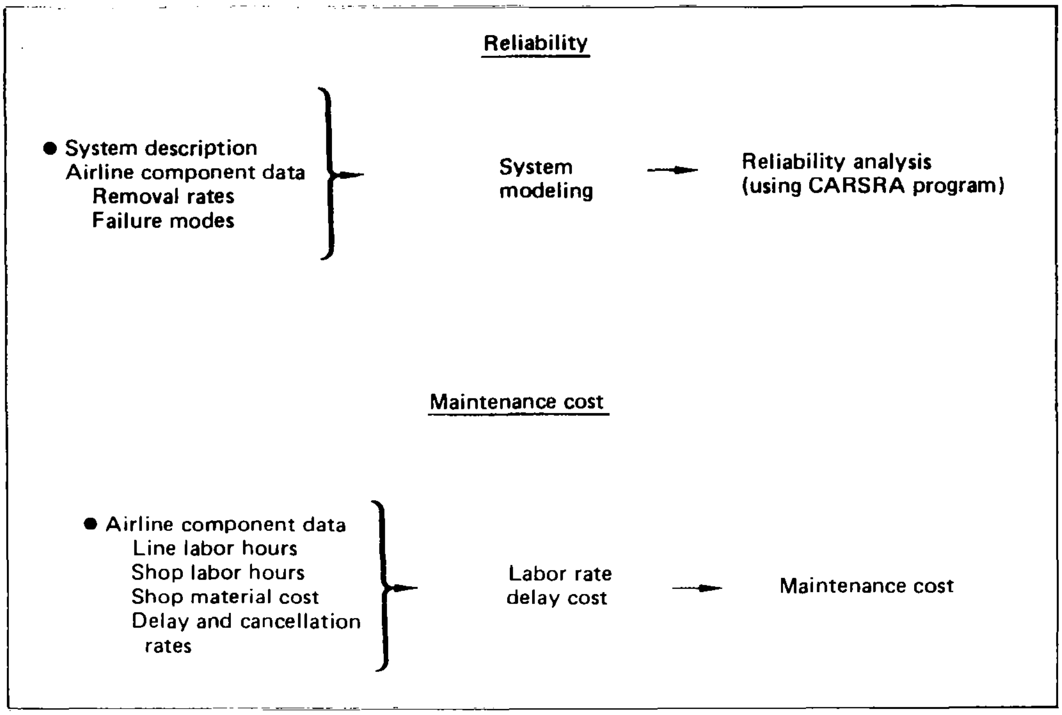


Figure 21. Analysis Approach

747 PRIMARY FLIGHT CONTROL SYSTEM
RELIABILITY AND MAINTENANCE STUDY
RELIABILITY ANALYSIS

Contractor and airline records covering component and system malfunctions over 7 years of 747 in-service operations by 15 airlines provided a comprehensive base for evalauation of system reliability. Each system was evaluated to establish the conditions that could cause loss of functions as described in the table. Probability of failure was determined using the historical records. Results are summarized in Table 4. The multiplicity of control paths, power sources, and control surfaces present in the 747 gives the primary flight control systems, elevator, lateral control, and rudder control great failure tolerance. The loss of function probability reflects these high levels of redundancy in the design.

The stabilizer trim and spoilers used as speed brakes also were evaluated, although these are considered secondary control functions.

Table 4. Reliability Analysis Results

	Elevator control	Lateral control	Rudder control	Stabilizer trim	Speed brakes
Control surfaces	4 panels	2 aileron panels 10 spoiler panels	2 panels	1 panel	8 spoiler panels
Hydraulic systems available	4	4	4	2	3
Loss of function Definition: Loss of actuation to these panel combinations	Both inboard panels, or inboard and outboard panel on same side	Both inboard ailerons and more than 5 spoilers, or 1 inboard aileron and more than 7 spoilers	Both upper and lower panels	Control surface	More than 5 panels
Failure probability for 4-hr flight	0.22×10^{-10}	0.21×10^{-10}	0.11×10^{-9}	0.53×10^{-7}	0.57×10^{-6}

747 PRIMARY FLIGHT CONTROL SYSTEMS RELIABILITY AND MAINTENANCE STUDY MAINTENANCE ANALYSIS

Two categories of maintenance are of interest as a data base: scheduled and unscheduled.

Scheduled maintenance includes inspsection of control cables and mechanisms, and is performed at each "C" check. This is a periodic check of the airplane to ensure continued airworthiness. It is anticipated that scheduled maintenance will be greatly reduced for airplanes incorporating electrical devices for control purposes. Maintenance on electrical equipment is usually accomplished on an unscheduled basis that is less costly, item-by-item.

Unscheduled maintenance cost consists of: 1) labor expense at the line stations for corrective actions generated by scheduled maintenance inspections and flight reports; 2) overhaul shop maintenance for components including both labor and material costs; and 3) delay and cancellation costs that include extra crew costs, passenger handling costs, and lost passenger revenue.

Results of the maintenance analysis are shown in Table 5. They show higher expenses for the primary functions, elevator, lateral and rudder control. Hydraulic actuators were found to be high in cost items.

Total unscheduled maintenance was found to be \$3.94 per flight hour, of which 60% or \$2.41 per flight hour, was due to labor and material costs for line and overhaul shop categories. Delays and cancellations accounted for 40% or \$1.53 per flight hour.

Scheduled maintenance costs of 19¢ per flight hour were estimated from detailed planning requirements, because airline data at the component level were not available.

Table 5. Maintenance Analysis Results

	Costs per flight hour		
	Labor and material	Delays and cancellations	Total
Unscheduled maintenance			
Elevator control	$0.26	$0.17	$0.43
Lateral control	1.06	0.56	1.62
Rudder control	0.88	0.48	1.36
Stabilizer trim	0.14	0.21	0.35
Speed brakes	0.04	0.04	0.08
Flight controls—general	0.03	0.07	0.10
Total	$2.41	$1.53	$3.94
Scheduled maintenance (estimated) —total			$0.19

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CR-3220		

4. Title and Subtitle
Selected Advanced Aerodynamic and Active Control Concepts Development—Summary Report

5. Report Date
January 1980

6. Performing Organization Code

7. Author(s)

8. Performing Organization Report No.
D6-46705

9. Performing Organization Name and Address
Boeing Commercial Airplane Company (BCAC)
P.O. Box 3707
Seattle, Washington 98124

10. Work Unit No.

11. Contract or Grant No.
NAS1-14742

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Contractor Report
10 Aug 1977–9 Aug 1979

14. Sponsoring Agency Code

15. Supplementary Notes
This report summarizes the results of work conducted under Contract NAS1-14742
Langley Technical Monitor: David B. Middleton
Topical Report

16. Abstract

A summary is presented of results obtained during analysis, design and test activities on six selected technical tasks directed at exploratory improvement of fuel efficiency for new and derivative transports. The work included investigations into the potential offered by natural laminar flow, improved surface coatings and advanced high lift concepts. Similar investigations covering optimum low-energy flight path control, integrated application of active controls and evaluation of primary flight control systems reliability and maintenance are also summarized. Recommendations are included for future work need to exploit potential advancements.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
EET Program Advanced Aerodynamics Active Controls Surface Coatings Reliability and Maintenance	FEDD Distribution Subject Category 05

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	53	

*Available: NASA's Industrial applications centers